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Executive Summary Report of Work Accomplished on the Corrosion-Fatigue Assessment Program

March 2008

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EXECUTIVE SUMMARY REPORT OF WORK ACCOMPLISHED ON THE CORROSION-FATIGUE ASSESSMENT PROGRAM

Contract No.: N00014-06-C-0643

March 31, 2008

TECHNICAL REPORT

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Foreword

This report describes the technical work accomplished during the period from June 2003 through 31 March 2008, for the Naval Air Warfare Center – Aircraft Division, under three separate contracts (Contract Numbers: F42620-00-D-0039, delivery order 0011; F42620-00-0028, delivery order 0040; and N00014-06-C-0643). Engineering Software Research and Development, Inc. (ESRD) and The Boeing Company were the major subcontractors on the all three contracts and Dr. Paul Hoffman was the Contract Monitor.

Mr. Wally Hoppe of the UDRI Structural Integrity Division was the Principal Investigator for these contractual efforts. Mr. Robert Andrews (until 30 June 2007) and Mr. Michael Bouchard (after 1 July 2007), Division Heads of the Structural Integrity Division, served as overall Program Managers. Ms. Ollie L. Scott and Ms. Gloria Hardy provided program management services. The following UDRI employees contributed to the major accomplishments on this contract: Dr. Bill Braisted, Mr. Garry Abfalter, Ms. Jennifer Pierce, Mr. Brian Frock, Mr. Bob Olding, and Dr. Ray Ko. Ms. Andrea Snell formatted and edited the document. Additional contributors included: Mr. Dave Rusk of NAVAIR; Dr. Barna Szabo, Dr. Ricardo Actis, and Mr. Brent Lancaster of ESRD; and Dr. Krishnan K. Sankaran, Dr. Herb Smith, Jr., and Mr. Bert Neal of Boeing.

Section 1
Synopsis

In June 2003, UDRI was placed on contract, as prime, to lead in an effort to study the effect that corrosion has on the fatigue life of high-strength steels in Navy applications. In September 2005, UDRI was placed under contract to AES to continue the effort begun by the earlier program. In September 2006, UDRI was placed under contract to continue the effort begun under the two previous contracts. The Navy Corrosion-Fatigue Assessment Program was designed to ensure reliability and supportability of current and emerging Naval aircraft by providing requisite engineering support to evaluate issues relevant to corrosion-fatigue of airframe components. The purpose of these contracts was to develop tools that can be used to specify the maintenance options for corroded components and to provide a sound engineering basis for selecting the best fleet maintenance options. Essentially, the program was to provide quantifiably justified maintenance criteria for environmentally induced damage (i.e., corrosion) in high-strength steels.

The overall objectives of these programs included the following outcomes:

- A corrosion severity classification scheme (i.e., cosmetic, mild, and severe) tied to component reliability or reduction in fatigue life,
- Corrosion metrics associated with these corrosion classifications,
- Nondestructive inspection (NDI) methods, requirements, and procedures for measuring corrosion severity via these corrosion metrics; and
- Component disposition tools and procedures to make engineering disposition decisions based on detailed corrosion profiles and validated life prediction assessment models.

The plan to meet these overall objectives consisted of the following activities:

- Determining the effect of corrosion on fatigue life of high-strength steels through corrosion-fatigue experiments supported by other baseline tests;
- Developing corrosion metrics based on surface profiles, correlating metrics to life reduction, and using these results to develop corrosion classification criteria;
- Investigating and developing NDI methods and procedures that can determine corrosion severity via correlations of NDI to corrosion metrics; and

- Developing physics-based analysis methods to determine effective stress concentration factors for corrosion, correlating the analysis predictions to corrosion-fatigue tests, and validating on component tests.

These research tasks are part of a multi-year, multi-contract program. The first contract was initially funded in June 2003 for one year, followed by a second year of funding and extensions to August 2006. The second contract was awarded in September 2005 for one year and extended to September 2007. The third and final contract was awarded in September 2006 and extended to 31 March 2008. The entire effort lasted four years and ten months. The University of Dayton Research Institute was prime on the first contract, with Engineering Software Research and Development (ESRD), Inc. and The Boeing Company as subcontractors. UDRI was a subcontractor to AES on the second contract with ESRD, Boeing, and Computational Mechanics, Inc. as second-tier subcontractors under UDRI. UDRI was, again, the prime contractor on the third contract to ONR with ESRD and The Boeing Company as subcontractors. This document summarizes activities and accomplishments under these three contracts.

Section 2

Summary of Work Accomplished on the Program

2.0 Purpose and Objectives of the Program

Navy carrier-based aircraft employ high-strength steel in many components, including landing gear and arrestment shanks. The service life of these components is generally defined by fatigue caused by load cycles. However, aircraft must operate in coastal environments that result in corrosion-assisted fatigue of airframe components. The effect of corrosion on component fatigue life has not been quantified. This problem is most acute for high-strength steel, such that it is important to determine how to quantify remaining life considering both cycle-dependent and time-dependent damage mechanisms. A quantifiable metric must be established to estimate remaining life due to the presence of corrosion.

The Navy Corrosion-Fatigue Assessment Program was designed to ensure reliability and supportability of current and emerging Naval aircraft by providing requisite engineering support to evaluate issues relevant to corrosion-fatigue of airframe components. The purpose was to develop tools that can be used to specify the maintenance options for corroded components and to provide a sound engineering basis for selecting the best fleet maintenance options. Essentially, the program was to provide quantifiably justified maintenance criteria for environmentally induced damage (i.e., corrosion) in high-strength steels.

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- Developing physics-based analysis methods to determine effective stress concentration factors for corrosion, correlating the analysis predictions to corrosion-fatigue tests, and validating on-component tests.

2.1 First Contract

This section summarizes activities under the first of the three contracts supporting the overall objectives of the program. During the first contract, NAVAIR, UDRI, and its team members designed, manufactured, and subsequently tested in fatigue 54 AF 1410 corrosion-fatigue test specimens. Each specimen had been prepared according to a test matrix that included growing corrosion according to a UDRI-developed protocol for various exposure times: zero, 3, 6 and 12 hours, respectively, using the electrochemical method developed for this purpose. Subsequent to growing corrosion in circular patches, the specimens were cleaned in a Turco solution to remove the corrosion products without further altering the specimen surface. After this, the specimens were ultrasonically inspected. Later specimens were also eddy current inspected. The final step prior to fatigue testing provided high-resolution surface profiles of the corroded surface via a white light interference microscopic system. The test matrix also stipulated load conditions covering a range of loads of interest. During testing, marker bands were introduced on any fracture surface by varying the R-value of the load in a predetermined manner. In addition, some specimens were monitored by penetrent inspections to identify crack initiation sites. As of the end of the first contract, all AF1410 specimens in the first set had been fatigued until failure. Several specimens had been subjected to additional investigation to attempt preliminary validation of models being developed.

Also, during the first contract, a significant effort was put forth to develop corrosion-fatigue models. Initial efforts were directed at implementation of finite element analysis (FEA) methods to calculate stress concentration due to the corrosion based on detailed profiles of the corrosion surface. This approach was discovered to be intractable, in that the FEA mesh required to capture the fine details of the corrosion surface made computation so excessively long as to be

impossible. Further efforts to simplify the surface profile produced unreliable FEA results, given that the simplifications that were designed to reduce computation time required more manageable meshes, which were then not representative of the actual surface profile. Similarly, efforts to simplify the corrosion details by assuming simpler geometric profiles, such as rounded cones, produced stress concentrations that were overly dependent on small changes in the assumed shape of the corrosion feature.

In parallel with these efforts, a study was conducted to develop so-called global/local models, which attempted to provide the requisite detail at a local level, while using less detail at the global level. Unfortunately, these approaches were also unsuccessful.

In a related study, a pit metric was developed that could estimate the stress concentration of a semi-ellipsoidal pit with a simple formula based on the dimensions of the principal axes of the pit and accounting for load direction. This simple formula was used in further developments later in the program.

When faced with the intractable nature of the FEA methods to the problem of calculating the stress concentration of a corroded surface, UDRI took an innovative tact to the problem by decomposing the surface into two-dimensional spatial frequency components. The stress concentration for each component was then estimated and the net effect of all components was determined by an inverse Fourier Transform. The theoretical basis for this admittedly approximate method to determine stress concentration is documented in the final report of the first contract on this program. Also included in that report are results of case studies performed to compare this so-called elasticity approach to FEA results for special cases. These studies defined practical limits for the applicability of the elasticity solution, which happen to be realistic for the levels of corrosion of interest on this program. That is, the levels of corrosion seen in the specimens tested on this program fell well within the region that should produce small errors in the estimation of stress concentration. There is, to be sure, a residual concern over this approach – or any approach – that is limited by the resolution of the surface profile. However, the extremely small features that would produce large stress concentrations were found to be mitigated by a notch size effect.

Near the end of the first contract, the elasticity approach to estimation of stress concentration was tested by comparing the location of crack initiation sites on corroded specimens with

the high-stress regions found from the elasticity solution applied to the profiles generated by the white light interference microscopic system on the same surfaces. The results on these preliminary checks were exceptionally promising and indicated that, while not all high-stress points cracked, all cracks did initiate in high-stress regions, and very near the peak stress in that local area. Additional validation of this model would have to wait until the second contract.

An issue arose during the development and execution of the first set of AF1410 corrosion-fatigue tests (Set A specimens). The associated specimens had been grit blasted and were suspected to have a resultant residual stress. After X-ray diffraction measurements confirmed this suspicion, a decision was made to manufacture a second set of AF1410 specimens. The manufacture of these specimens was started during the first contract.

It was also of interest to extend the methods being developed to other high-strength steels, such as 300M. However, previously conducted tests on a USAF program suggested that 300M would be extremely sensitive to corrosion attack, possibly due to the introduction of intergranular corrosion. A decision was made to test only nine 300M corrosion-fatigue specimens to confirm the results of the USAF study. Creation of these specimens was started on the first contract on the Navy Corrosion-Fatigue program. Aermet 100 was also selected for study. Specimen manufacture and preliminary tests on this material were primarily the focus of the third contract.

A nondestructive evaluation (NDE) investigation was also conducted on the first contract. After studying several methods to address the problem, it was concluded that the most promising NDE method is ultrasound. Subsequently, a series of ultrasonic measurements were made of various corroded surfaces. Included in these experiments were angle beam and normal incidence pulse-echo techniques using amplitude, time-of-flight, and frequency domain techniques. Normal incidence time-of-flight and Fourier phase slope methods were found to be the most promising of the techniques.

During the first contract, ESRD conducted a number of tasks that corresponded to the overall program goals. Initially, they performed a preliminary study of two-dimensional analyses of corroded surface representations. They also carried out finite element analyses of idealized representations of corrosion features, concluding that the stress concentration is highly sensitive to the assumed idealization and its dimensional parameters. Later, ESRD evaluated the UDRI

elasticity approach by comparing finite element models of simple surface features to the predictions of the elasticity model, finding that the approach works well for low-order terms of the Fourier expansion. Finally, ESRD modeled an F-18 arrestment shank.

Also, during the first contract, Boeing completed several tasks as part of its subcontract. They provided the team with a summary of experiences with regard to cleaning corrosion from steel coupons and summarizing the effects of the corrosion exposure environment on fatigue life. They also used optical microscopy to characterize the surface topography of a number of corrosion time-of-exposure wafers provided by UDRI. In an effort to identify candidate corrosion severity metrics for the program, Boeing compiled surface roughness statistics for the time-of-exposure wafers, plotting these as a function of exposure time. This study included a review of previous Boeing research on AF1410 corrosion-fatigue specimens and a collection of additional fracture surface measurements. In order to assist ESRD in the development of finite element tools, Boeing provided raw profilometry data from aluminum and AF1410 samples collected on earlier programs. They also provided a description of a proposed progression of corrosion from a pit to crack initiation, growth, and failure. Boeing also critiqued various accelerated corrosion growth approaches. In addition, the potential for manufacture of micro-machined features in fatigue test specimens was reviewed. In particular, Boeing examined the feasibility of using micro tools or micro laser machining techniques. A survey of Boeing's St. Louis engineering organizations was made to find instances of corrosion in steel structures in aircraft. They found that the F-15 nose landing gear has experienced corrosion, as well as the following F-18 parts: the shock strut cylinder, the arresting hook, the main landing gear lever, and the wingfold transmission. A small study was conducted describing the stress concentration of a hemispherical pit, which was thought to well-describe the local corrosion topography. A software tool for profilometry roughness analysis was created that uses surface height profiles as an input. Additional tools were included in the software to provide for flexibility in filtering and processing the surface profiles. Boeing also assessed several surface roughness metrics for suitability to correlate to fatigue life once corrosion-fatigue test data became available. Finally, Boeing participated in a round-robin evaluation to test the ability of the various organizations (NAVAIR, UDRI, and Boeing) to produce consistent quantitative fractography measurements for a series of corrosion-fatigue test specimens. Their measurements compared well with those of the other organizations, quailfying them to take these measurements on future specimens.

2.2 Second Contract

As it turned out, the second program contract significantly overlapped the timeframe of the first. Activities on the second contract focused on completion of AF1410 Set A and Set B tests, extending the modeling effort to reliability models for life prediction, developing corrosion metrics, preparation of 300M and Aermet 100 specimens (including preliminary tests on these materials), and the development of an implementation scheme.

To finish the analysis of the AF1410 Set A corrosion-fatigue tests, each fracture surface on the specimens was compared to the corrosion profile on the adjacent surface to identify the corrosion feature that initiated the crack. Dimensional measurements were taken of each corrosion feature and used to estimate stress concentration factors. Simple life predictions based on these estimates were compared to actual life measured in the fatigue tests.

Baseline and corrosion-fatigue tests were conducted in a second batch of AF1410 specimens (Set B). The corrosion-fatigue specimens were designed to exclude the grit blasting and also had smoother surfaces than Set A specimens. As a result of both of these facts, the test matrix included lighter corrosion exposure levels: zero, 1.5, 3, and 6 hours, respectively. As was true of the first set, this set was prepared in the same way, including ultrasonic and eddy current, as well as white light interference measurements of the surface profile. After fatigue testing, each specimen was examined to microscopically ascertain the number of cycles to crack initiation and to measure the dimensions of the critical feature that initiated the crack.

A small number of 300M corrosion-fatigue specimens were manufactured for the purpose of verifying the results of the earlier USAF study showing that 300M could tolerate very little corrosion without losing the majority of its fatigue life. Other associated tests were conducted in anticipation of these fatigue tests. Unfortunately, once fatigue testing was initiated and as fracture surfaces were examined, it became apparent that the batch of 300M that was used for these specimens, including earlier NAVAIR strain-life specimens, was contaminated with titanium inclusions. This contamination rendered all test specimens and previous test results of little value. At this point, these activities on 300M were terminated.

In the interest of extending the methods developed on this program to other materials, quantities of Aermet 100 were purchased and the manufacture of test specimens was initiated.

A major objective of this program was to develop modeling techniques to predict the effect that corrosion-induced surface roughness has on fatigue life. As mentioned above, an elasticity approach had been developed on the first contract to estimate the stress concentration due to corrosion. On the second contract, the results of this method were compared to the stress concentration calculated on pits using FEA and the UDRI pit metric. It was found that, while the elasticity approach could identify spots of high stress, it did not always find stress concentrations in precise agreement with FEA.

In addition to this finding, attempts to make life predictions directly from the stress concentration map from the elasticity model were unsuccessful. In particular, UDRI attempted to make life predictions based on the stress concentration maps by treating each pixel in the map as having a certain probability of failure that was based on extensions of Weibull's formalism, accounting for area effects in the same way Weibull accounted for specimen length. The probability of failure of each pixel was calculated using the stress concentration, the stress-strain curve, a fit to the Coffin-Mason relationship for strain-life data, Morrow's factor, and an extension of the Weibull formalism to account for pixel size. A statistical manipulation then produced the probability of failure (to crack initiation in this case) for all pixels in the corrosion patch. Preliminary trials were encouraging, but additional test cases revealed that the method was not always conservative in its predictions.

Subsequent to the above discoveries, NAVAIR developed the Equivalent Stress Riser (ESR) model, which models the life – not of pixels, but of individual pit-like features in the corrosion identified by the elasticity model. The stress concentration for each feature is estimated using the UDRI pit metric, as improved by ESRD's extension to account for both differences between FEA results and the pit metric and pit orientation with respect to load direction. In the ESR model, the probability of failure is calculated from strain-life data and a Peterson notch sensitivity factor, which moderates the effect of the stress riser by a factor dependent on the size of the notch. In particular, notches with smaller root radii are hypothesized to have smaller effects on life than notches with the same stress concentration, but larger root radii. The cumulative effect of all features is handled probabilistically. A set of algorithms was developed on the program to search through the stress concentration map to find regions of interest (ROIs) with high stress concentration. An ellipsoid is fit to each ROI and the root radii are estimated. Tests of

the ESR model on the corrosion-fatigue specimens have shown a consistent conservativeness in the life predictions. The question of how to deal with this conservativeness was a topic for the third contract.

In parallel with efforts to develop life prediction models, a study of various statistical metrics for corrosion severity was conducted. In particular, standard and novel roughness statistics were calculated and compared to corrosion-fatigue test results to investigate the effectiveness of each candidate metric as a measure of both corrosion severity and effect on fatigue life. Standard roughness metrics included R_a, the mean of the absolute difference between the surface height and the mean surface height, and R_q, the standard deviation of the surface height (or more accurately, the root-mean-square of the surface height). Variations on these metrics included scaling the metric by the applied load, and constructs involving the stress concentration values. While some of these novel metrics showed improved correlations to reduction in fatigue life, the improvements were marginal. R_q and R_a seem to provide the most robust metrics for surface roughness; however, there remains a need to account for the local applied load. In addition, studies were carried out to understand the effect of spatial resolution on the metric values and on correlation to reduction in fatigue life. This work anticipates the ultimate implementation of low-resolution NDE methods to screen components and to categorize corrosion severity. Down-sampled and filtered white light surface height profiles were used to calculate surface roughness metrics, which were then compared to the same metrics determined from full-resolution surface height profiles.

Finally, during the second contract on the Navy Corrosion-Fatigue Assessment Program, an implementation strategy was developed. This scheme is described by a flow chart starting with a visual inspection of the component on-board an aircraft carrier. If corrosion is observed, it is cleaned and an inspection performed. The relatively low resolution of this inspection prohibits a detailed application of the equivalent stress riser model; however, the inspection can be used to calculate corrosion metrics, such as R_a or R_q, and then to classify the corrosion as cosmetic, mild, or severe. If the corrosion is cosmetic, it will have no significant impact on component life and the component can be cleaned and coated (to prevent corrosion) and returned to service. If the corrosion is deemed to be severe, then the component is removed from service; the reduction in fatigue life is too great to allow the component to remain in service. If the corrosion is mild, then a replica is made of the corrosion, which is then sent to the depot for a high-resolution surface

height mapping and subsequent analysis. At this point, the Equivalent Stress Riser model is applied in order to make a disposition decision concerning the component.

During the second contract, ESRD performed a number of tasks as part of the overall research on this program. A study was conducted of white light interferometry topography data for potential metrics. In this study, ESRD developed a MATLAB/Visual Basic Application for statistical analysis of corroded specimens. They then compared a full-resolution white light data set to a 1/16th data set. They also investigated different filtering approaches and the issues involved. The root-mean-square (RMS) metric was used to characterize corroded surface profiles and an RMS field measure was compared to crack initiation locations for the AF1410 Set A specimen number 16. ESRD also proposed an alternative life prediction method based on an equivalent crack size approach. Another important contribution to the program was their analysis of the micro-features that have been machined into specimens for the purpose of better understanding the effects of feature shape and material variations expected in fatigue tests. Each feature was designed by ESRD to have the same stress concentration value, but different shapes were used – some in different orientations. The features were conical, ellipsoidal, and pill-shaped. ESRD performed StressCheck® finite element analysis on these shapes to confirm that the stress concentration was identical for each one. ESRD also performed a number of case studies of different pit scenarios and refined the ellipsoidal pit metric developed on this program by accounting for pit orientation and including a small correction term in the calculation of stress concentration from the pit metric. Finally, ESRD incorporated the capability to include variable materials properties in StressCheck®.

Boeing also played an important role on the second contract. In particular, they milled the micro-features into the micro-machined fatigue specimens and performed quantitative fractography measurements of the crack initiation sites after these specimens were tested in fatigue by UDRI. They also studied various candidate metrics for the AF1410 Set A and B specimens, accounting for applied load in their analysis. Finally, Boeing has been involved in efforts to define and execute verification and validation of the models developed on this program. Specifically, Boeing reviewed the NAVAIR equivalent stress riser model software as part of code verification. They also examined various test cases in the model.

Computational Mechanics was also a subcontractor on the second contract to study the possibility of using boundary element analysis to model corrosion and determine stress concentration factors. To do this, they used a global/local approach to include both the global characteristics of the corrosion and the fine detail around stress risers.

2.3 Third Contract

Just as there was much overlap in schedule between the first and second contracts on this program, there was much overlap between the second and third. During the third contract, the program focused on AF1410 arrestment shank life predictions and fatigue tests, continued preparation of Aermet 100 tests (some of which were started), investigations into methods to calibrate the ESR model, development of a grid method of corrosion classification and life prediction, and verification and validation of the various models developed on the program. Verification and validation included both a series of tests on AF1410 micro-machined fatigue test specimens, as well as manufacture and blind tests of cadmium-plated AF1410 corrosion-fatigue test specimens with associated life predictions from the ESR model.

Earlier in the program, replicas were made of the inside surface of three real AF1410 arrestment shanks that had been taken out of service. Each shank was found to have corrosion on this inner surface. A fixture was manufactured that would allow the curved replicas of the inner shank surface to be scanned with the white light interference microscope to map the surface profile for study on the program. Due to the curvature of the replicas, only very narrow strips of the surface profiles could be captured without repositioning the replica. While the fixture simplified this process, each replica requires weeks of scanning on the white light interference microscope to construct an accurate and complete profile of the surface height variations. Therefore, only selected portions of the replicas have been scanned. In the meantime, the shanks were fatigue tested to failure. Life predictions were compared to test results.

As mentioned above, Aermet 100 test specimen manufacture continued on the third contract. A set of 74 corrosion-fatigue specimens was fabricated and polishing begun. Other specimens for baseline material tests were also made, including strain-life specimens. The baseline and strain-life tests were begun on this program, but these tests and the corrosion-fatigue tests will need to be completed on a subsequent program.

During the previous contract, an equivalent stress riser model was developed. It was discovered that the model gave consistently conservative estimates of life. For this reason, methods were pursued to calibrate the model to produce less-conservative life predictions. One method to calibrate the model was based on an extreme value statistical approach. The effort was not conclusive and additional study is recommended.

In an effort to establish an implementation scheme that includes an NDE method to classify corrosion, a grid method for life prediction was proposed. In this method, an appropriate surface roughness metric would be determined based on surface height profiles within elements of a grid overlaid on the surface of the specimen or component. During development, these surface height metrics would be determined from white light interference microscope profiles, but in practice, this would need to be determined from NDE methods, such as surface height profiles determined ultrasonically. During this contract, a fit was established between the grid statistics determined from the ultrasonic and the white light measurements. In practice, the proposed approach would require that grid statistics be found for a component using the NDE method, from which white light statistics would be calculated using the fit found on this program. The white light statistics would then be used to make a life prediction based on an extension of the equivalent stress riser model to the grid metrics. A corrosion classification could then be made to categorize the corrosion as cosmetic (no impact on life), mild (a moderate impact on life calling for additional analysis with the original equivalent stress riser model), or severe (unacceptable impact on life).

An important component of this program has been verification and validation of the life prediction models. Verification refers to steps to confirm that the software code accurately reflects the physics being modeled (code verification) and that the calculations conducted by that code are correct (calculation verification). Validation refers to the steps taken to confirm that the model predictions are experimentally correct. A verification and validation plan was created and considerable work accomplished on this program. Of particular importance were two sets of validation experiments conducted on this program. A set of fatigue specimens were created with micro-machined features produced in the gauge section of each specimen, which were designed to have identical stress concentration factors, but of different shapes. The test specimens were all identical in order to have replicate tests, so as to reveal feature and material effects. The second

test was a blind validation experiment on AF1410 cadmium-plated corrosion-fatigue specimens. Each plated specimen was sanded in a small patch in the center of the gauge section in order to compromise the cadmium plate (otherwise, corrosion would not grow), and then the specimens were exposed to a salt fog containing SO_2 for a set period of time (a different method of growing corrosion than previously used in the corrosion-fatigue tests on this program). Subsequently, the corrosion products were removed, surface height profiles determined, and the specimens fatigue tested until failure. Each fracture surface was examined to ascertain the number of cycles to crack initiation. The surface height profiles were used to make life predictions to compare to the actual, experimentally determined fatigue lives.

As in the first two, ESRD played a significant role on the third contract. Primarily they were involved in verification and validation tasks for the models developed on this program. Similarly, Boeing contributed significantly to the software verification of the equivalent stress riser model. They also conducted time-of-exposure studies for the cadmium-plated corrosion-fatigue validation test specimens, eventually growing corrosion on these specimens. Finally, they took additional fractography measurements on the micro-machined test specimens, specifically focusing on secondary crack initiation sites.

Section 3
Document Cross Reference

The following documents have been prepared to capture the work conducted on this program across the three contracts. First, there is a final report for each contract [1-3]. In addition, a report has been prepared that discusses the models developed on the program [4]. Another report describes the corrosion-fatigue tests conducted on AF1410, concentrating on the AF1410 Set B (or Batch B) tests [5]. Shank test results are included in another report [6]. This section reviews the contents of these reports.

"Navy High-Strength Steel Corrosion-Fatigue Modeling Program", Final Report, UDR-TR-2007-00039 documents all tasks accomplished on the first contract under this overall program. This includes a summary of previous corrosion-fatigue programs and an NDE literature search. There is a description of all testing conducted on that contract, which included baseline mechanical and corrosion-fatigue tests on AF1410. It also describes the supportive studies and investigations including:

- corrosion growth experiments,
- examination of various corrosion cleaning methods,
- measurements designed to confirm that the selected corrosion growth method did not adversely affect the base material,
- a review of different corrosion characterization methods,
- a preliminary corrosion metric study,
- a study of approaches to create replicas of the corrosion surfaces,
- surface profile measurements of corrosion found inside real arrestment shanks, and
- tests to establish methods of determining crack dimensions as a function of cycles using marker bands.

In addition to the development of these tools that were used throughout the program, the report describes the NDE investigation and progress, as well as the significant developments early in the program towards the creation of a model to predict the effect on life of corrosion-induced surface roughness. Finally, both the ESRD and Boeing final reports for this first contract are included as appendices in their entireties.

"Improved Navy Maintenance Through Corrosion-Fatigue Assessment Program", Final Report UDR-TR-2008-00064, documents much of the progress achieved on the second contract in this program. This report includes additional results for the AF1410 Set A specimens and a description of the 300M tests that were started on the program explaining the material problems encountered with this batch of steel. A summary of a study of standard candidate surface roughness metrics is included along with some novel hybrid metrics that account for applied stress. The report also discusses the results of a study concerning the effect that spatial resolution of the surface height profile measurements has on these metrics.

The modeling efforts begun on the new contract were further advanced on the second contract with the development of region-of-interest analysis tools. One method investigated to predict fatigue life is described in the report, along with results of some preliminary tests of this method. In light of the marginal results of this pixel-based method, the equivalent stress riser model was developed, which used the outcome of the ROI analysis to predict the contribution of each ROI to the overall specimen life. The report briefly describes the equivalent stress riser model and makes reference to the ancillary report that has additional detail (see below).

The second-year final report includes details of the ultrasonic and eddy current measurements with instrument parameter settings as well as calibration and scanning procedures. From the surface height maps generated from these NDE scans, surface roughness statistics were calculated and compared to the same statistics determined from the white light surface profiles.

The second-year final report also includes a description of the implementation plan developed on the program. In this scheme, after an inspector has observed by eye the presence of corrosion, he will perform an NDE inspection and use the results of that inspection to classify the corrosion as cosmetic, mild, or severe. Components with cosmetic corrosion will be cleaned and returned to service, components with severe corrosion will be removed from service, and replicas will be made of the corroded surface of components with mild corrosion. These replicas will be sent to a depot to map the surface height profiles and the equivalent stress riser model will be used to estimate the remaining life of the component. A decision to return or remove the part from service will be made based on the results of this modeling analysis.

Finally, the report contains the final reports of ESRD, Boeing, and Computational Mechanics. Also included in the appendix is a description of ESRDs variable materials property tools and how to use these tools with StressCheck.

“Corrosion-Fatigue Assessment Program”, Final Report UDR-TR-2008-00069, documents much of the progress accomplished on the third contract on this program. A set of Aermet 100 corrosion-fatigue test specimens were prepared, as well as baseline materials property and strain-life specimens; preliminary testing was conducted with some of these specimens. The micro-machined and cadmium-plated specimens were tested in fatigue on this third contract. These specimens and tests are described in the final report.

The report also includes a discussion of the efforts to calibrate the equivalent stress rise model to reduce or eliminate the observed conservativeness in the life predictions. A grid model is also presented that is proposed for use with surface roughness statistics derived from the NDE measurements and an extension of the equivalent stress riser model. A study was performed and the results presented that correlates these surface roughness statistics based on the NDE measurements to those derived from white light interference microscopy measurements.

A key component of the program has been verification and validation of the models developed. A section of this final report is devoted to these tasks and their status.

Finally, this appendices of this report include the ESR and Boeing final reports.

“Modeling and Prediction of Corrosion-Fatigue Failures in AF1410 Steel Test Specimens”, Navy report: NAWCADPAX/TR-2008/60, captures the details of the equivalent stress riser model, associated theory, predictions, and evaluation of these predictions with test data. A section reviews the corrosion-fatigue test specimen data, followed by a section motivating the use of notch-based modeling for corrosion and notch sensitivity model calibration. The elasticity approach to estimating stress concentration of a corroded surface is described and then the region-of-interest analysis methods are given. The report explains how the so-called equivalent stress riser model is used to predict fatigue life, and then this method is used to predict lives for the micro-machine and cadmium plated validation test specimens. The report includes discussions on stress gradient effects and an extension to the equivalent stress riser model using surface

roughness metrics in localized elements of a grid overlaying the corroded region. Status of verification and validation activities is also given.

Results comparing the life predictions to the test data are provided. Correlations between k_{fc} values from ROIs and specimens are discussed. Life predictions (after the fact) for AF1410 Set A and Set B corrosion-fatigue specimens are compared to experimentally determined fatigue lives. Similarly, life predictions for the micro-machined test specimens are reviewed in light of test data. Likewise, life predictions and test results are compared for the cadmium-plated corrosion-fatigue validation tests. Finally, a discussion of the application of the equivalent stress riser model is given.

"Results of Fatigue Tests of Bare AF1410 Steel Unnotched Flat Plates with Surface Corrosion Damage", Navy report: NAWCADPAX/EDR-2008/10, documents the various aspects of tests performed on baseline and corrosion-fatigue test specimens made from AF1410, with a particular emphasis on the Set B specimens. The report is designed to be a standalone summary of these tests and starts with a description of the specimen preparation, test, and post-test processing methods. This includes methods to manufacture and prepare the specimens, growing and cleaning corrosion from the specimens, making surface height profiles of the corrosion patches, fatigue testing, and post-fatigue fracture and corrosion feature characterization. The report also presents results of the mechanical property and corrosion-fatigue tests with a discussion of the signifycance of these results.

"Analysis and Testing of Fleet Corroded F/A-18C/D Arrestment Shanks," Final Report, NAWCADPAX/TR-2008/9, May, 2008, is a report dedicated to the discussion of life predictions and test results of full-article fatigue testing of F/A-18C/D arrestment shanks, which were found to have surface corrosion on the inner surface. Corrosion cleaning, surface preparation, and surface characterization tasks performed by UDRI on the arresting shank lateral damper surfaces are described. The procedures used to create replicas of the corroded surfaces and WLI image scans of the replicas are detailed. A full description of the ESRD efforts to create a representative FEM of the shank corroded area is included, along with model refinements resulting from comparisons of the predicted strains to strain survey results of the test articles. Load spectrum development, test fixturing, strain surveys, and shank testing performed at the NAVAIR Structural Test Facility

(AIR 5.4.9.4.1) at NAS Patuxent River, MD were defined. Descriptions of the fatigue failure mode for each tested shank are listed, along with surface crack locations and fractographic images of the critical cracks. The test results for the three shanks indicated that fretting damage at the hook end of the shank was the principle failure mode. No cracks occurred in the corroded regions of two test shanks, while the third had a fatigue crack originating from a small patch of significant corrosion just aft of the lateral damper sleeve region. However, this crack did not fail the shank.

Section 4
Summary, Conclusions, and Recommendations

The objectives of this program and its associated contracts have been met, specifically:

- A corrosion severity classification scheme (i.e., cosmetic, mild, and severe) tied to component reliability or reduction in fatigue life has been proposed, based on surface roughness statistics calculated for elements of a grid overlaying the corrosion patch and a modification of the equivalent stress riser model.
- Corrosion metrics associated with these corrosion classifications have been identified, which includes R_a and R_q defined over the grid elements. The grid model must include the effects of local applied stresses.
- Nondestructive inspection (NDI) methods, requirements, and procedures for measuring corrosion severity via these corrosion metrics have been outlined. Additional studies have considered the effects of resolution on the determination of the metric statistics and correlations of the NDE-determined grid statistics, as well as those determined from the white light interference profiles over the grid elements.
- Component disposition tools and procedures to make engineering disposition decisions based on detailed corrosion profiles have been developed. In particular, the equivalent stress riser (ESR) model has been created and tested in a number of ways. Life predictions from this model have been found to be conservative. Additional development, verification, and validation are warranted.

The plan to meet these overall objectives consisted of the following activities:

- Determining the effect of corrosion on fatigue life of high-strength steels through corrosion-fatigue experiments supported by other baseline tests,
- Developing corrosion metrics based on surface profiles, correlating metrics to life reduction, and using these results to develop corrosion classification criteria,
- Investigating and developing NDI methods and procedures that can determine corrosion severity via correlations of NDI to corrosion metrics, and
- Developing physics-based analysis methods to determine effective stress concentration factors for corrosion, correlating the analysis predictions to corrosion-fatigue tests, and validating on cadmium-plated corrosion-fatigue tests.

Initial investigation of the ESR model demonstrates that an empirical approach to corrosion surface damage that builds on traditional notched fatigue analysis methods can be utilized to generate probabilistic life predictions that have substantial engineering value in assessing the residual fatigue life of corroded AF1410 steel components. Further work to refine the ROI search algorithm methods and to investigate the sensitivity to varying levels of corrosion and white light interference microscopy scan resolution is warranted. However, the approach does capture the significant corrosion features that cause fatigue cracking in most cases, especially for more severely corroded surfaces.

Overall, there has been much progress in developing tools for characterization and quantification of the effects of corrosion-induced surface roughness on fatigue life. A master implementation plan was developed and reported in the final report of the second contract [2]. Several of the objectives need additional development in order to be ready for implementation in the fleet.

- Further development and test is needed on the grid model, including setting realistic corrosion classification limits.
- Verification and validation must be completed for the model and all associated components of the model.
- Inspection technologies that can be implemented in the field or aircraft carrier must be developed that meet or exceed the requirements demonstrated on this program.
- The methods developed on this program should be extended to other materials, particularly Aermet 100, by performing corrosion-fatigue tests and making life predictions using the specimens manufactured on this program.
- A method is needed to rapidly inspect shank replicas in the depot with a resolution that rivals the white light interference microscope.

Section 5
References

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4. Rusk, D., et. al., “Modeling and Prediction of Corrosion-Fatigue Failure in AF1410 Steel Test Specimens”, Navy report: NAWCADPAX/TR-2008/60.
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